

On Optically Thick Condensations
in Planetary Nebulae

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ABSTRACT

The time-scale of optically thick condensations in pressure equilibrium with the low density gas constituting the rest of a planetary nebula is comparable to the life-time of the nebula. Some observational aspects of such condensations are discussed.

The time-scale of condensations not in pressure equilibrium with the remainder of a planetary nebula has been shown to be short compared to the life-time of the nebula (Williams, 1969). It is possible for a situation similar to that of an HI cloud immersed in an HII region (Spitzer, 1968) to exist in a planetary nebula. In the case of a planetary nebula, the ionized material leaving the condensation interacts with the rest of the nebula and therefore, cannot freely expand. In the absence of non-gas dynamic forces, the condensation-nebula system will dynamically seek pressure equilibrium. This behavior will lead to the destruction of an optically thin condensation; but because the equilibrium temperature in a low density gas exposed to an external source of radiation is primarily a function of

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of optical thickness, an optically thick condensation can still exist after pressure equilibrium is achieved between the condensation and the rest of the nebula.

The limiting case of a very optically thick condensation in pressure equilibrium with the lower density nebular gas in which it is submersed is of interest because it lends itself to a simple analysis which allows some general statements to be made about its observational properties. Computations show that the temperature inside such a condensation is on the order of 100°K , while that outside is on the order of 10000°K . The density ratio corresponding to pressure equilibrium is therefore about 200. Although carbon, magnesium, and other elements with low ionization potentials provide some ionization in the interior of the condensation, the temperature and electron density are very low, so that most of the radiation must arise from the boundary between the condensation and the rest of the nebula.

The existence of such condensations depends upon a source of diffuse radiation external to the condensation, presumably that of the remainder of the nebula, which provides the radiation necessary for the ionization boundary on the side hidden from the central star. If the external source of diffuse radiation is weak the condensations might be elongated radially away from the central star, depending on the geometry involved. Because of the complicated geometry necessary for the proper treatment of diffuse radiation quantitative results based on model condensations are presently unavailable. However, estimates of typical values of the ionization boundary thickness t_B and the distance t_{10} which corresponds to a change of 10 in the optical depth inside the condensation for a sequence of typical nebular and condensation densities together with a nominal sequence of sizes are presented in Table 1.

If the condensation and nebula remain in pressure equilibrium as the nebula evolves the density of the condensation ρ_c will be almost directly proportional to that of the nebula ρ_n as long as the condensation is optically thick. Thus, $\rho_c \approx k \rho_n$, where $k \approx 200$, and $\dot{\rho}_c/\rho_c \approx \dot{\rho}_n/\rho_n$, so that the time scale for the condensation is about the same as that of the nebula. The evolution of the condensation size depends on whether or not there is mass exchange between it and the rest of the nebula. If there is none, then $\dot{r}_c/r_c = \dot{\rho}_c/3\rho_c$, and it follows that the size of the optically thick part of the condensation remains a constant fraction of the nebular radius. The nebular radii R_n and condensation diameters D_c given in Table 1 were chosen on the basis of no mass exchange and show a hypothetical evolutionary sequence.

As the nebula and condensation evolve together, the decreasing density causes the boundary between them to thicken, so that the size of the visible part of the condensation grows relative to the rest of the nebula. The effect of central star evolution would be to produce a thinner boundary, but the results of Sofia and Hunter (1968) indicate that central star evolution may be neglected when considering nebular dynamics. The density decrease associated with the nebular evolution allows ionizing radiation to reach farther into the condensation boundary ($R_s \propto \langle N_e^2 \rangle^{-1/3}$, where R_s is the Stromgren sphere radius), so that there is a net mass loss from the condensation to the nebula. However, the contribution of the material leaving the condensation to the optical thickness of the boundary and the surrounding lower density gas tends to regulate the mass loss. Because the assumption that the velocity of the nebular gas relative to the condensation is the sound velocity in the nebula (cf. Spitzer, 1968) is not compatible with the

assumption of approximate pressure equilibrium, it is not possible to specify an appropriate boundary structure and thereby deduce the rate of mass loss without detailed computations. Also, because the spectrum of such a condensation depends on the details of the boundary structure, it is not possible to quantitatively predict the spectrum. However, some qualitative statements about the spectral appearance may be based on the fact that the existence of an optically thick condensation in pressure equilibrium with the rest of the nebula depends upon a source of diffuse radiation external to the condensation.

Only diffuse radiation, which is strongly concentrated toward the continuous absorption edges of H, He, and He^+ , reaches the part of the condensation boundary which is optically thick to the stellar radiation. Therefore, this part receives very little O^+ and N^+ ionizing radiation and the integrated spectrum of the condensation should have relatively enhanced [OII] and [NII] lines. Also, because the abundance of O^{++} is low and cooling due to oxygen diminished, the temperature of that part should be higher than that inferred from the average energy of an absorbed photon (cf. Harrington, 1968). The spectrum in both the forbidden and permitted lines of other ions should be sensitive to the external source of diffuse radiation, as well as the geometry and distribution of density through the boundary of the condensation. Because the radiation longward of 912\AA for hydrogen or 1102\AA for carbon, which determines the temperature inside an optically thick condensation, is almost independent of position, the variation in density required to provide a zero pressure gradient inside the condensation is negligible. Therefore, the condensation can take on almost any configuration as long as it is smaller than the external source of diffuse radiation.

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TABLE 1

ESTIMATED CONDENSATION PROPERTIES

$N_n(\text{cm}^{-3})$	$R_n(\text{cm})$	$N_c(\text{cm}^{-3})$	$D_c(\text{cm})$	$t_{10}(\text{cm})$	$t_B(\text{cm})$
10^4	1.0×10^{17}	2×10^6	1.0×10^{15}	10^{12}	6.0×10^{14}
10^3	2.15	2×10^5	2.15	10^{13}	2.8×10^{15}
10^2	4.64	2×10^4	4.64	10^{14}	1.3×10^{16}
10	10.0	2×10^3	10.0	10^{15}	6.0×10^{16}
1	21.5	2×10^2	21.5	10^{16}	2.8×10^{17}